Subaru Spectroscopy of the Interacting Type Ia Supernova SN 2002ic: Evidence of a Hydrogen-rich, Asymmetric Circumstellar Medium

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ABSTRACT

Optical spectroscopy of the Type Ia supernova SN 2002ic obtained on 2003 June 27.6 UT, i.e., ~ 222 rest-frame days after explosion, is presented. Strong H emission indicates an interaction between the expanding SN ejecta and an H-rich circumstellar medium (CSM). The spectrum of SN 2002ic resembles those of SNe 1997cy and 1999E. The three SNe also have similar luminosities, suggesting that they are the same phenomenon and that the CSM is also similar. We propose a new classification, Type IIa SNe, for these events. The observed line profiles and line ratios are measured and discussed within the ejecta-CSM interaction scenario. The emission in H Balmer, [O III], and He I lines, and in permitted Fe II blends, resembles the spectra of the Type IIn SN 1987F and of Seyfert 1 galaxies. A high-density, clumpy CSM is inferred. Strong, very broad [Ca II]/Ca II and [O I]/O I emissions imply that not all the outer SN ejecta were decelerated in the interaction, suggesting that the CSM is aspherical.

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1. INTRODUCTION

Hamuy et al. (2003) reported strong Fe III, Si II, and S II features in the early-time spectra of SN 2002ic and classified it as a Type Ia supernova (SN Ia). However, strong Hα emission was also observed. The detection of Hα is unprecedented in an SN Ia. (For reviews on SN spectra, see Filippenko 1997). The emission was broad (FWHM > 1000 km s^{-1}), suggesting that it was intrinsic to the SN. Hamuy et al. (2003) suggested that it arose from the interaction between the SN ejecta and a dense, H-rich circumstellar medium (CSM), as in SNe IIn (e.g., Chugai 1991; Chevalier & Fransson 1994). If this interpretation is correct, SN 2002ic may be the first SN Ia to show direct evidence of the circumstellar (CS) gas ejected by the progenitor system, presenting a unique opportunity to explore the CSM around an SN Ia and the nature of the progenitor system.

In this Letter, we present optical spectroscopy of SN 2002ic obtained more than 200 days after explosion, and discuss it within the context of the ejecta-CSM interaction.

2. OBSERVATIONS AND RESULTS

Observations were carried out on 2003 June 27.6 UT with the Faint Object Camera and Spectrograph (Kashikawa et al. 2002) attached to the Cassegrain focus of the 8.2 m Subaru Telescope. For the red observation (5900 – 10200 Å), we used a 300 groove mm^{-1} grism (centered at 7500 Å) and an order-cut filter O58. For the blue observation (3800 – 7000 Å), we used another 300 grooves mm^{-1} grism (centered at 5500 Å) and no filter. A 0″.8 width slit was used under moderate seeing conditions (FWHM $\simeq 0″.6 - 0″.7$), resulting in a spectral resolution $\lambda/\Delta\lambda \sim 650$ (~ 460 km s^{-1}). The total exposure time was 1680 s for each observation. The flux was calibrated using observations of BD+28°4211 (Massey and Gronwall 1990). A systematic error of ~ 0.1 mag is caused by the insufficient width of the slit compared with the seeing size. Although all data were taken in polarimetric mode, the signal-to-noise ratio is not high enough for sufficiently accurate polarimetry ($\lesssim 0.2$ %). Therefore, in the following only the flux data are discussed.

The spectrum is shown in Figure 1, after correction for redshift ($z = 0.0666$; Hamuy et al. 2003) and Galactic extinction ($E_{B-V} = 0.06$; Schlegel et al. 1998). The epoch is ~ 222 rest-frame days after explosion, which we assume occurred on 2002 November 3 UT (Hamuy et al. 2003). The spectrum has a brightness of $m_V \sim 19.0$. In other words, the SN is only

~ 1.5 mag fainter than at maximum light (Hamuy et al. 2003), while a normal SN Ia at similar epochs would have faded by ~ 5 mag with respect to maximum light (Figure 2).

The spectrum is strikingly similar to those of the peculiar SNe 1997cy (Turatto et al. 2000) and 1999E (Rigon et al. 2003), which were classified as Type IIn. (See also Wang et al. 2004.) SN 2002ic would also have been so classified, had it not been discovered at an early epoch when it appeared to be a genuine SN Ia. Hamuy et al. (2003) also noticed similarities to SN 1997cy in an earlier spectrum (~ 71 days after explosion).

The $UBVRI$ light curves (LCs) of the three SNe are also similar (Figure 2). To construct the LC of SN 2002ic, we first integrated the Subaru spectrum. This yielded $L = (5.8 \pm 0.6) \times 10^{42}$ ergs s^{-1}, assuming a distance of 307 Mpc. The bolometric correction thus estimated was used to convert m_V at earlier phases in Hamuy et al. (2003) and the late-time MAGNUM telescope (Yoshii 2002) photometry into rough bolometric luminosities.

3. SPECTRAL ANALYSIS

The Hα profile was decomposed using three Gaussians (Figure 3, *top left*). (We used Gaussians for mathematical convenience, although real component profiles can be different.) A narrow core (FWHM ~ 1000 km s^{-1}) is unresolved owing to low instrumental resolution. The intermediate component has FWHM ~ 4800 km s^{-1}. It may develop from the ~ 1800 km s^{-1} component seen at earlier phases (Hamuy et al. 2003). The broad blue wing centered at ~ 6350 Å is likely [O I] $\lambda\lambda6300,6364$ (FWHM ~ 26000 km s^{-1}). The integrated fluxes are 4×10^{-15}, 1.5×10^{-14}, and 3.2×10^{-14} ergs s^{-1} cm^{-2}, respectively.

Broad [O I] $\lambda\lambda6300, 6364$ is also present in SNe 1997cy and 1999E. [O I] lines seen in a few SNe IIn (e.g., Fransson et al. 2002) are narrower than 4000 km s^{-1} and much weaker. [O I] $\lambda5577$ is not obvious. Its potential location, marked by an arrow in Figure 1, is well in the smoothly declining part of the $\sim 5100 - 5600$ Å feature.

The Hβ $\lambda4861$ – [O III] $\lambda5007$ complex was decomposed with four Gaussians (Figure 3, *top right*). The two Hβ components have FWHM ~ 1700 and 4000 km s^{-1} and flux of $\sim 8 \times 10^{-16}$ and 9×10^{-16} ergs s^{-1} cm^{-2}, respectively. The unresolved [O III] $\lambda5007$ component (FWHM ~ 500 km s^{-1}) has a flux of $\sim 1.4 \times 10^{-16}$ ergs s^{-1} cm^{-2}. The expected intensity of [O III] $\lambda4959$ is only one-third that of $\lambda5007$ (Osterbrock 1989). So the ~ 4950 Å feature (FWHM ~ 6000 km s^{-1}) is mainly due to Fe II multiplet 42.

Our spectrum shows a possible [O III] $\lambda4363$ line (Figure 3, *bottom right*), as in SNe 1997cy and 1999E. A tentative Gaussian fit gives FWHM ~ 1200 km s^{-1} and a flux of $\sim 1.7 \times 10^{-16}$

ergs s^{-1} cm^{-2}, which are likely overestimates. The feature to the left is also unresolved: it seems not to be Hγ λ4340; the SN 1999E spectrum (*open circles*) does not show Hγ.

We decomposed the 7300 Å feature into He I λ7065, [Ca II] $\lambda\lambda$7291, 7324/[O II] $\lambda\lambda$7320, 7330, and O I λ7774 (Figure 3, *bottom left*). The FWHMs are $\sim$ 3000, 18,000, and 10,000 km s^{-1}, and the fluxes are $\sim 6\times10^{-16}$, 1.2×10^{-14}, and 2.3×10^{-15} ergs s^{-1} cm^{-2}, respectively. He I λ5876 is weak (FWHM $\sim$ 1400 km s^{-1}, flux $\sim 2\times10^{-16}$ ergs s^{-1} cm^{-2}), as in SN 1997cy.

The strong emission near 8500 Å is a blend of the Ca II IR triplet and O I λ8446 (FWHM $\sim$ 13000 km s^{-1} and flux $\sim 4.7 \times 10^{-14}$ ergs s^{-1} cm^{-2}). A broad feature to the red could be weak O I λ9265. The Ca II H and K flux is $\sim 1 \times 10^{-14}$ ergs s^{-1} cm^{-2}.

The lines we have identified can be divided into two groups based on their width. One group, comprising the H Balmer, [O III], and He I lines, have unresolved cores (FWHM $\lesssim$ 1000 km s^{-1}) and, in the case of Hα and Hβ, components of intermediate width (FWHM $\sim 3000 - 5000$ km s^{-1}). The other group includes broad [Ca II]/Ca II and [O I]/O I lines (FWHM > 10000 km s^{-1}). These lines do not show a narrow component.

We believe the unresolved components are CSM emissions, likely from a progenitor wind, as in SNe IIn (e.g., Fransson et al. 2002). R. Kotak & W. P. S. Meikle (2004, in preparation), using high-resolution spectroscopy, saw a P Cygni line with absorption velocity ~ 100 km s^{-1} atop the Hα core. Rigon et al. (2003) measured a similar P Cygni velocity for Hα (~ 200 km s^{-1}) in SN 1999E. The intermediate components of Hα and Hβ may be formed by multiple Thomson scattering of narrow emissions in CSM clouds of $n \gtrsim 10^8$ cm^{-3} (Wang et al. 2004). The [O III]-emitting region may have $n \sim 10^7$ cm^{-3} ($T \sim 10^4$ K), near the critical density of the [O III] $2p^2$ ^1S level, as implied by the comparable flux of the possible [O III] λ4363 line (Osterbrock 1989).

The total Hα luminosity, $L(\mathrm{H}_\alpha) \sim 2 - 3 \times 10^{41}$ ergs s^{-1}, may imply $\sim 0.4 - 3 M_\odot$ of high-density ionized H ($\sim 10^8 - 10^9$ cm^{-3}) in the CSM, assuming case B recombination (see also Wang et al. 2004). Our Balmer decrement $[L(\mathrm{H}_\alpha)/L(\mathrm{H}_\beta) \sim 10]$ is much steeper than expected for case B. Either collisional processes are important or other Balmer photons are absorbed and cascaded into Hα, or both. In either case, a high density is implied.

We suggest that the broad O/Ca lines are emitted by the SN Ia ejecta. In the W7 model for SNe Ia (Nomoto, Thielemann, & Yokoi 1984), the outer C/O layer has $v > 12000$ km s^{-1} and a typical density of $\sim 10^5$ cm^{-3} around 200 days, assuming free expansion. This is consistent with the detection of [O I] $\lambda\lambda$6300, 6364 but not of [O I] λ5577, which suggests $n < 10^8/t(\mathrm{days})$ cm^{-3} if $T \sim 10^4$ K (see Figure 7 in Leibundgut et al. 1991). The weakness of the [Ca II] $\sim$ 7300 Å line with respect to the IR triplet may suggest that the density is not as low. However, the flux ratio F_{7300}/F_{8500} in SN 1997cy actually decreases with time

and density. Perhaps the ~ 8500 Å feature is dominated by Lyβ-pumped O I $\lambda8446$ at later phases.

Parts of the outer ejecta must avoid strong CS interaction to retain high velocities and produce the broad O and Ca emissions (powered by X-ray/UV radiation from the interaction region). The velocity of the shocked region and the preshocked ejecta is too low to explain the width of these lines. According to hydrodynamical simulations (T. Suzuki et al. 2004, in preparation), the pre-shocked ejecta have velocities less than 7000 km s^{-1} at ~ 100 days after explosion and less than 4000 km s^{-1} at ~ 200 days, and the shocked ejecta are decelerated to similar velocities. We suggest that the CSM is concentrated near the equator, so that the ejecta near the pole do not strongly interact with it (see also Section 5).

We suggest that the features near 4300, 4600, 4950, and 5300 Å (marked by circles and one arrow in Figure 4) are broad blends of Fe II multiplets 27; 38 and 37; 42; and 49, 48, and 42, respectively. They strikingly resemble the Fe II permitted emissions in Seyfert 1 galaxies (Osterbrock 1989; see also Filippenko 1989 for similar conclusions in SN IIn 1987F). They may come from the cool shell in the reverse shocked region or, more likely, from the dense CSM clouds, suggesting a density $\gtrsim 10^9$ cm^{-3}.

4.   SPECTRAL COMPARISON WITH OTHER TYPES

In Figure 4, we compare the late-time spectra of SNe 2002ic, 2000cx (Ia), 1998bw (Ic), and 1988Z (IIn). Strong [Fe III]/[Fe II] blends dominate the normal SNe Ia spectra (e.g., Liu, Jeffery & Schultz 1997) and this suggests low density and high ionization relative to SN 2002ic where we find permitted Fe II lines. SNe Ic show very strong Mg I] $\lambda4571$ (Mazzali et al. 2001). This line could blend with the Fe II feature near $4400 - 4700$ Å in SN 2002ic, but SNe 1997cy and 1999E disfavor a strong Mg I] contribution since in their spectra the central wavelength is ~ 4640 Å.

The spectrum of the SN IIn 1988Z also looks different from that of SN 2002ic, although both show strong Hα emission. In SN 1988Z, broad [O I] $\lambda\lambda6300, 6364$ and [Ca II] $\lambda\lambda7291, 7324$ are absent, as in other SNe IIn (Filippenko 1997), while Ca II IR/O I emission is weak. The broad Fe features near 4600 and 5300 Å are also absent in SN 1988Z.

5.   DISCUSSION

The currently preferred model for SNe Ia is the thermonuclear explosion of a C+O white dwarf (WD) in a binary system, reaching the Chandrasekhar limit via either accretion from

a normal companion (the SD scenario, which is generally favored) or merging with another WD (the DD scenario). (For recent reviews, see Nomoto et al. 2000; Livio 2000.)

The SD scenario predicts the presence of an H/He-rich CSM. The discovery of strong CSM interaction in SN 2002ic may prove that this scenario does exist in nature. SNe 1997cy and 1999E may also be CS-interacting SNe Ia. However, such events are rare. Solid observational evidence of CSM has not yet been found in other SNe Ia (Lundqvist et al. 2003).

Our spectral analysis suggests a high-density H I-emitting CSM ($n \sim 10^8 - 10^9$ cm^{-3}); so this is probably clumpy. Assuming the CSM was formed in a progenitor wind, we relate the mass-loss rate $\dot{M}$ and the wind velocity u to the Hα luminosity, through $L(\mathrm{H}_\alpha) \sim 1 - 5 \times 10^{39}$ $(\dot{M}/10^{-2}$ M$_\odot$ yr$^{-1})^2$ $(u/100$ km s$^{-1})^{-2}$ $r_{16}^{-1} f^{-1}$ ergs s^{-1}, where r_{16} is the radius of the CSM shock in units of 10^{16} cm and f is the CSM filling factor. For $u \sim 100$ km s^{-1} and $f \sim 0.01$, $\dot{M}$ can be as high as $\sim 10^{-2}$ M$_\odot$ yr^{-1}. The case B emissivity used here may underestimate $L(\mathrm{H}_\alpha)$ by $\sim 50\%$, considering that most Hβ photons may have cascaded to Hα.

We have identified high-velocity lines (FWHM $\gtrsim 10^4$ km^{-1}) emitted in the ejecta of SN 2002ic. Based on the hydrodynamical model of T. Suzuki et al. (2004, in preparation), we suggest an equatorially concentrated structure for the CSM to explain the coexistence of these lines with the strong CS interaction. Such a geometry is not unexpected for the mass loss from a binary system or for stars approaching the end of the asymptotic giant branch (AGB). A preexisting clumpy disk was also suggested by Wang et al. (2004), based on spectropolarimetry.

Is $\dot{M} \sim 10^{-2}$ M$_\odot$ yr^{-1} too high for the SD scenario? The highest $\dot{M}$ observed in AGB stars is between 10^{-3} and 10^{-4} M$_\odot$ yr^{-1} (Iben 1995); $\dot{M}$ in our estimate is scaled as u. The bulk of the CSM may be near the equator and at low velocity (~ 10 km s^{-1}), which cannot be resolved. The observed Hα P Cygni, dominated by the emission component, could be produced by some high-velocity CSM ($\gtrsim 100$ km s^{-1}) along the pole, which should be close to our line of sight. Similar wind patterns have been observed in some symbiotic stars (e.g., Solf & Ulrich 1985), which have been suggested as candidates for SN Ia progenitors.

Further observations and modeling are required to understand the nature of the CSM giving rise to this type of event, which may be classified as "Type IIa." Suggestions include a common envelope (Livio & Riess 2003), WD accretion wind (Hachisu et al. 1999), and the superwind from an AGB star exploding as a "type 1.5" event (Hamuy et al. 2003).

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Fig. 1.— Spectra of SNe 2002ic (*thick lines*; $\sim$ 222 d), 1997cy (*thin lines*; Turatto et al. 2000), and 1999E (*dashed line*; Rigon et al. 2003).

Fig. 2.— Comparison of the $UBVRI$ LC of SN 2002ic with those of SNe 1997cy (Turatto et al. 2000), 1999E (Rigon et al. 2003), and the normal SN Ia 1994D (Contardo, Leibundgut & Vacca 2000).

Fig. 3.— Gaussian decomposition of line profiles. Solid squares show the observed profiles, thin lines are the Gaussian components, and thick lines are the combined Gaussian profiles. Open circles show [O III] $\lambda4363$ in SN 1999E.

Fig. 4.— Spectra of SN 2002ic (*thick lines*; $\sim$ 222 d) and SNe Ia 2000cx (*top*; Li et al. 2001), Ic 1998bw (*middle*; Patat et al. 2001), and IIn 1988Z (*bottom*; Turatto et al. 1993).

Fig. — Spectral line fits showing Hα, [O I] 6300,6364, Hβ, [O III] 5007, Fe II, He I, [Ca II] / [O II], O I, and [O III] 4363 with Rest wavelength on the horizontal axes.